

# Cosmic ray spectrum by energy scattered by EAS particles in the atmosphere and galactic model

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## Abstract

The differential energy spectrum of cosmic rays from Cherenkov radiation measurements in EAS in the energy range of  $10^{15} - 10^{20}$  eV has been compared with an anomalous diffusion model for the particles in interstellar space having fractal properties (Lagutin et al., 2001). The close association between experimental data and calculated “all particle” spectra in form at  $E_0 \sim (10^{15} - 10^{18})$  eV is found. In this case, the average mass composition of cosmic rays calculated by five components does not contradict the average mass composition from experimental data which was obtained by several of EAS characteristics in that energy region.

## I. INTRODUCTION

The discovery of irregularities in the cosmic ray energy spectrum at the energy of  $\sim 3 \times 10^{15}$  eV (Khristiansen et al., 1956 [1]) and  $\sim 8 \times 10^{18}$  eV (Krasilnikov et al., 1978 [2, 3, 4]), the detection of sharp decreases in the cosmic ray intensity at  $E_0 > 5 \times 10^{19}$  eV (Greisen-Zatsepin-Kuzmin effect, 1966 [5, 6]) at the EAS arrays in Yakutsk, HiRes (USA), AUGER (Argentina) are the most important achievement in the investigation of the superhigh and ultra-high energy cosmic rays in recent years. Such a character of spectrum turn out to be associ-

ated directly with processes in interstellar space, namely, with the origin, acceleration and propagation of cosmic rays in the Galaxy and beyond. The interpretation of these experimental facts using the different models of cosmic ray origin still remains to be answered.

In this paper the comparison of the cosmic ray energy spectrum by EAS Cherenkov light measurements at the Yakutsk array [7, 8] with the calculations according to an anomalous diffusion model of cosmic rays in interstellar space [9] is performed.

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## II. METHOD TO CONSTRUCT THE EAS SPECTRUM

The showers at the Yakutsk array are selected with the central register by both scintillation and Cherenkov “masters” [10, 11]. The all showers registered form the database of the Yakutsk EAS array.

To construct the spectrum in energy, scattered by EAS particles in the atmosphere (Cherenkov radiation) the following selection criteria of showers are used: a) a shower core is to be placed within a perimeter of the array for the giant showers and near a center of the array for the showers with  $E_0 < 10^{18}$  eV. The showers whose cores are near the observation station  $R \leq 60$  m are excluded from a sampling; b) the probability to register a shower by Cherenkov photons is  $W_{\text{ch}} \geq 0.9$ ; c) a zenith angle is less than one-half of an aperture of Cherenkov detector, i.e.  $\theta < 55^\circ$  in the case of the detector of the first type and  $\theta < 60^\circ$  for the second type detector; d) a transmission coefficient of the atmosphere is  $\geq 0.60$  for the wave length of 430 nm.

Thus, more than 60000 showers with  $E_0 \geq 10^{17}$  eV and 300000 showers with  $10^{15} \leq E_0 \leq 10^{17}$  eV were recorded in the database. To construct the spectrum, the showers were selected by the classification parameter  $Q(R = 150)$ , i.e. by Cherenkov light flux density at a distance 150 m from a core, which was proportional to the primary shower energy. The mea-

surement accuracy for  $Q(R = 150)$  in the individual showers was  $\delta = \Delta Q(R = 150)/Q(R = 150) \geq 15\%$ .

The estimation of the shower energy  $E_0$  is determined by a quasicolorimetric method which does not depend on the EAS development model. A basis of the method is experimental data about the Cherenkov light total flux,  $F$ , the total number of charged particles,  $N_s$ , and the total number of muons with  $E_{\text{thr}} \geq 1$  GeV,  $N_\mu$  [12, 13, 14]. The energy of individual showers is determined by the following formula:

$$E_0 = (9.1 \pm 2.2) \cdot 10^{16} \times Q(R = 150)^{0.99 \pm 0.02} \quad (1)$$

The intensity of cosmic ray flux in the given interval of EAS classification parameter is found as a ratio of the number of registered EAS events to  $S_{\text{eff}} \cdot T \cdot \Omega$ .

## III. RESULTS AND DISCUSSION

The differential energy spectrum of primary cosmic rays in the interval of  $10^{15} - 5 \times 10^{19}$  eV obtained from a totality of the all Cherenkov detector measurement data at the Yakutsk EAS array is shown on the Fig. 1. Our data confirm an irregularity of the spectrum of “knee” type in the energy range of  $(2 - 5) \times 10^{15}$  eV discovered in [1], and the irregularity of “ankle” type at  $E_0 \sim 8 \times 10^{18}$  eV. It is established that in the first case the spectrum in-

dex is  $\gamma = 2.7 \pm 0.1$  below the break and  $\gamma = 3.03 \pm 0.05$  at  $E_0 > 3 \times 10^{15}$  eV, and in the second case, the more sloping spectrum with  $\gamma = 2.6 \pm 0.3$  at  $E_0 > 8 \times 10^{18}$  eV is observed.

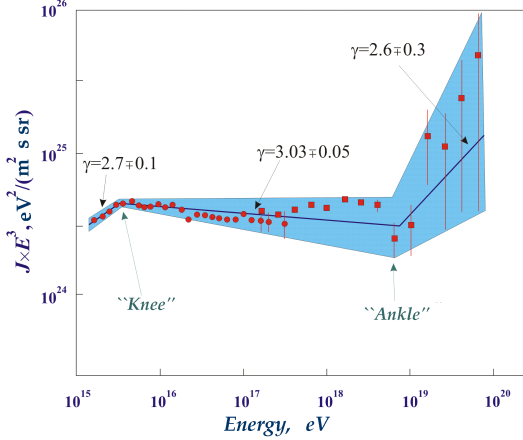


Figure 1: Energy spectrum of primary cosmic rays by measurement data of Cherenkov light at the Yakutsk complex EAS array.

For the period of continuous observations of Cherenkov radiation more than 30 years (10% relative to one year time of EAS registration with the scintillation detectors), the showers

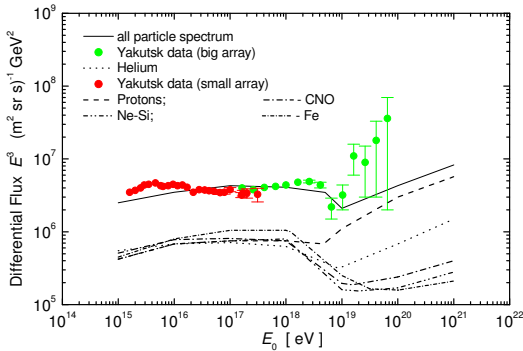


Figure 2: Differential cosmic ray intensity versus the energy. The points are Yakutsk array data, curves are the calculation from [9].

with  $E_0 > 6 \times 10^{19}$  eV did not detect. This fact confirms once more the GZK hypothesis [5, 6] about the sharp break in the cosmic ray energy spectrum at  $E_0 > 5 \times 10^{19}$  eV.

### The galactic model

The attempt to explain a form of obtained spectrum from the point of view of cosmic ray anomalous diffusion model and fractality of the Galaxy's magnetic field was made by Lagutin et al [9]. The basis for the cosmic ray propagation in the Galaxy is the following assumptions: a) after the generation in the sources, the particles move in fractal interstellar medium by means of two ways: the first way is "Levy flights", the second way is the motion along a spiral in the nonhomogeneous magnetic field, b) the particles exist during anomalous long time. The lifetime of particles is of a wide distribution and its tail is described by a power law  $q(t) \propto B \cdot t^{-\beta-1}, t \rightarrow \infty, \beta < 1$  (so-called "Levy trapping time"). Calculations of the spectrum were separately made for each of following groups of nuclei: p, He, CNO, N-Si, Fe. The resulting sum spectrum for the all particles is shown by a solid curve in Fig. 1. From the calculations it follows that the suggested model reproduces the irregularity in the energy spectrum of the "knee" type at  $E_0 \simeq 3 \times 10^{15}$  eV and also the irregularity of the "ankle" type at  $E_0 \simeq 8 \times 10^{18}$  eV. This model does not ex-

plain the behavior of a spectrum in the energy region of  $10^{17} - 10^{18}$  eV and the break of the spectrum at  $E_0 > 6 \times 10^{19}$  eV in more detail. The mass composition in the energy region of  $5 \times 10^{15} - 5 \times 10^{18}$  eV is some heavier than at  $E_0 \simeq 10^{19}$  eV, but this change is not very significant that is expected from an experiment (see Fig. 3).

### The galactic model with the sources of two types

In contrast to [9], in the paper [15] a scenario is considered, in which supernovae are the main sources of cosmic rays and the acceleration up to  $E_{\max} \simeq 105 \cdot Z$  GeV takes place in the shock fronts. The particle spectrum formed in this case can be presented in the form of  $S_{\text{SN}} \sim E^{-2} \theta(E_{\max} - E)$ , where the Heaviside function  $\theta(x)$  reflects qualitatively the presence of a sharp cut-off in the spectrum at  $E > E_{\max}$  [16, 17]. The new calculations fulfilled by the above scenario of particle generation in the sources of two different types under the assumption of anomalous diffusion of particles in inhomogeneous medium show that at some parameters the anomalous diffusion model describes satisfactorily the features of cosmic ray energy spectrum and mass composition up to  $E_0 \sim 10^{18}$  eV observed in an experiment. First of all, it refers to the fine structure of cosmic ray intensity change depending on the energy

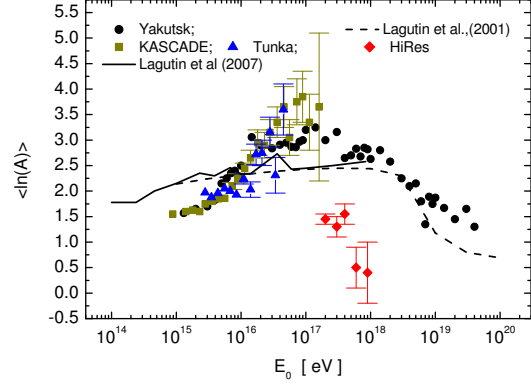


Figure 3: Mass composition of cosmic rays at super-high and ultrahigh energies. The curve is a calculation by Lagutin et al (2001) according to the anomalous diffusion model for cosmic ray propagation.

(see Fig. 1). By using these calculations, the sharp peaks in the mass composition depending on energy are also observed (see Fig. 3). In this connection, it is of interest to compare calculations in mass composition with experimental data obtained at the Yakutsk EAS big and small Cherenkov sub-arrays in recent years.

### Mass composition of primary cosmic rays

Fig. 3 presents the results in mass composition of primary cosmic rays of the Yakutsk array. The data were obtained in the framework of QGSJET-01 model and two-component mass composition (proton-iron nucleus). The several characteristics corresponding to the radial and longitudinal development of EAS are used in the analysis [18, 19, 20, 21, 22].

The value  $\langle \ln A \rangle$  in each case is determined

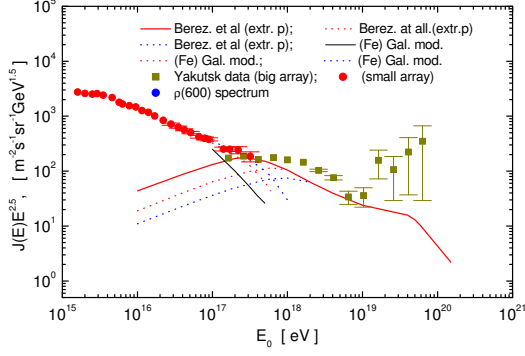


Figure 4: Comparison of the experimental spectrum with the calculated spectrum from [23] for the meta-galactic protons ( $E_0 > 5 \times 10^{17}$  eV) and galactic iron nuclei ( $E_0 = 10^{15} - 5 \times 10^{17}$  eV).

by using the interpolation method [24]. It is seen from Fig. 3 that the mass composition is varied up to heavy elements in the energy region of  $(2 - 5) \times 10^{17}$  eV and becomes more light beginning with  $E_0 \sim 3 \times 10^{18}$  eV.

The lines are the calculations according to the anomalous diffusion model for the propagation of cosmic rays in the Galaxy (Fig. 3, two sources) in the case of inhomogeneous galactic medium. In the first case, the monotone change in the mass composition up to  $E_0 \geq 3 \times 10^{18}$  eV is observed, after of which the mass composition becomes more light. In the second case, the complicated structure in the dependence of mass composition on the energy is observed, peaks for the nuclei of different mass in the energy region of  $10^{15} - 10^{17}$  eV are noticeable. According to a hypothesis [25] and calculations from [15], such an inhomogeneous structure can be formed by a near supernova. Our data (Fig. 3)

do not contradict to this hypothesis.

Such a sharp change of the mass composition in the energy region of  $5 \times 10^{16} - 5 \times 10^{17}$  eV is not explained in the framework of the galactic model and is likely associated with the existence of a transition boundary from galactic to meta-galactic cosmic rays. This conclusion is confirmed by calculations from [23], where a scenario of galactic and metagalactic origin of cosmic rays is considered. These calculations are shown in Fig.4 together with our experimental data. It can be seen from Fig. 4 that cosmic rays in the energy region of  $5 \times 10^{16} - 5 \times 10^{17}$  eV are most likely of galactic origin with the noticeable portion of heavy nuclei in the total flux.

It should be noted the estimations of cosmic ray mass composition in the region after the “knee”, obtained at the compact arrays, agree well with each other. The same cannot be said of the energy region of  $\sim 10^{18}$  eV (see Fig. 3) where HiRes array data point to more speedy enrichment of primary radiation by the light nuclei and protons as compared with the Yakutsk array data. The Yakutsk EAS array data, on the contrary, show the gradual change from the heavy to light composition (protons and He nuclei) at  $E_0 \sim 10^{19}$  eV. In both cases, data point to the existence of the tendency of “protonization” of primary cosmic rays at  $E_0 > 3 \times 10^{18}$  eV.

## Conclusions

Direct measurements of the cosmic ray energy spectrum in the region of ultrahigh energies (in energy scattered by EAS particles in the atmosphere) have confirmed the complicate form of spectrum. The spectrum becomes steeper at  $E_0 \geq 3 \times 10^{15}$  eV and more sloping at  $E_0 \geq 8 \times 10^{18}$  eV. A character of energy dependence of  $\langle \ln A \rangle$  by the Yakutsk EAS data point to the change of the mass composition of primary particles at singular points of cosmic ray energy spectrum. The value  $\langle \ln A \rangle$  rises with the energy after the knee up to its maximum equal to 3.5 at  $(2 - 5) \times 10^{17}$  eV and then it begins to decrease. Such an energy dependence of  $\langle \ln A \rangle$  does not contradict a hypothesis of cosmic rays propagation according to laws of the anomalous diffusion model in fractal interstellar medium (Lagutin et al., 2001). The value  $\langle \ln A \rangle$  at  $E_0 > 10^{18}$  eV decreases gradually and at  $E_0 \sim 10^{19}$  eV the mass composition consists of He nuclei and protons. The cosmic ray intensity beyond  $E_{\text{thr.}} > 6 \times 10^{19}$  eV de-

creases sharply and this effect is not described in the framework of the galactic model only. Such a character of spectrum does not contradict to the calculations by Berezhinsky et al [23] for the metagalactic model, in which the “ankle”, observed in the experiments on ultrahigh energy cosmic ray registration, can be produced by the proton component only arriving from the Metagalaxy. Thereby, the details of experimental spectrum form, for example, “dip”, i.e. the decrease of intensity at  $E_0 \times 10^{19}$  eV, are caused by, most likely, the interaction of extragalactic protons with a relic radiation photons ( $p + \gamma_{\text{CMB}} \rightarrow p + e^+ + e^-$ ). As a direct argument of this hypothesis, the anisotropy can be used which is related to the origin and sources of cosmic rays. Based on data of [26, 27, 28], at  $E_0 \geq 8 \times 10^{18}$  eV the weak correlation in the arrival directions of EAS with the Galaxy plane and the close correlation with the Supergalaxy plane are observed and that the quasars can be the possible sources of cosmic rays.

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